A Study of a High-Energy Gamma-ray Spectrum Produced by 9Be(α,nγ)12C Reaction to Diagnose the Escaping Helium from a Fusion Plasma

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A STUDY OF A HIGH-ENERGY GAMMA-RAY SPECTRUM PRODUCED BY $^{9}Be(\alpha, n\gamma)^{12}C$ REACTION TO DIAGNOSE THE ESCAPING HELIUM FROM A FUSION PLASMA

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ABSTRACT

Nuclear fusion reactor has been developed and studied all over the world in order to generate electricity. To demonstrate nuclear reactions in fusion reactors, an in-beam study has been conducted with a tandem accelerator at Kobe University. The gamma-rays generated by the reaction were measured with a high purity germanium detector. The angular dependence of the gamma-ray yield was measured, and the cross section of the reaction was discussed. The energy spectra of the gamma-rays were also measured. Since the excited nucleus in the reaction emits gamma-rays before the nucleus stops, the spectra of gamma-rays are affected by the Doppler effect. The Doppler shift and broadening were observed as functions of the detection angle. A computer simulation of these effects was conducted. The comparison of these effects were in agreement with the experimental results. Results suggest that there is a diagnostic capability for the escaping helium particles from the burning plasmas.

Keywords: gamma-ray measurement, Doppler effect, lost alpha diagnostics

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1. INTRODUCTION

Nuclear fusion reactors have been developed and studied all over the world. A nuclear reactor generates electricity, and it is expected to be the next power source. There are some candidates for the rector, one of which is a magnetic confined plasma device. The international thermonuclear experimental reactor, ITER, is a magnetic confined plasma type reactor, and it is under construction in south France. Nuclear fusion reaction occurs in the plasma, and the reaction is

$$d + t \rightarrow n + \alpha. \quad (1)$$

where d, t, n, and α denote deuterium nucleus, tritium nucleus, neutron, and helium nucleus, respectively. In order to generate and maintain the burning plasma it is essential to study plasma physics. A fusion product of helium particles can escape from plasma; understanding the behavior of these particles is useful when studying plasma confinement.

When escaping helium particles were incident on a plasma wall, it can react with beryllium nucleus in the wall. The reaction is

$$^{9}Be + \alpha \rightarrow {}^{12}C + n + \gamma\ . \quad (2)$$

The reaction generates gamma-rays and neutrons. Since measurement of the gamma-rays gives information about α particles, we obtain the plasma condition. The simultaneous measurement of the incident position and the incident angle of the α particle on the wall has a benefit for this diagnostics.

A diagnostic method was conducted by Kiptily et al. (2001, 2002, 2004, 2006) and Gin (2011). For the method, a scintillator detector was set on the vacuum vessel in LHD and the luminescence of gamma from incidence α was measured. The development of a scintillator system for ITER was reported by Nishiura (2010). As the scintillator is damaged by the radiation from the plasma, this method is difficult to use. If gamma-rays are measured on many points, then the diagnostics become better. A conventional gamma-ray camera does not have the detection sensitivity for this gamma-ray energy. Thus, a gamma-ray camera for high energy has been developed for this diagnostic (Nishiura 2014, Doi 2015).

In this study, to demonstrate the reaction, energetic helium was generated with a tandem accelerator and it was incident on a beryllium target. A similar in-beam study was reported by Kiptily (1991, 2010). The gamma-rays generated by the reaction were measured by a high-purity germanium detector (HPGe). The angular dependence of the gamma-ray yields and the energy spectra were measured. The Doppler shift and the broadening were observed. A computer simulation of these effects was conducted, and the results were compared and discussed.

2. EXPERIMENTAL PROCEDURE

To demonstrate the reaction in the plasma wall, energetic helium was generated with a tandem accelerator (NEC, model 5SDH-2) at Kobe University, and it was incident on a beryllium target. The gamma-rays generated by the reaction, ^{9}Be(α, nγ)^{12}C, was measured with a HPGe (EG&G, model GMX25P4-70) detector. The detection efficiency for 4.439 MeV gamma-ray is 8.4 %. The experimental set up is shown in Fig. 1.

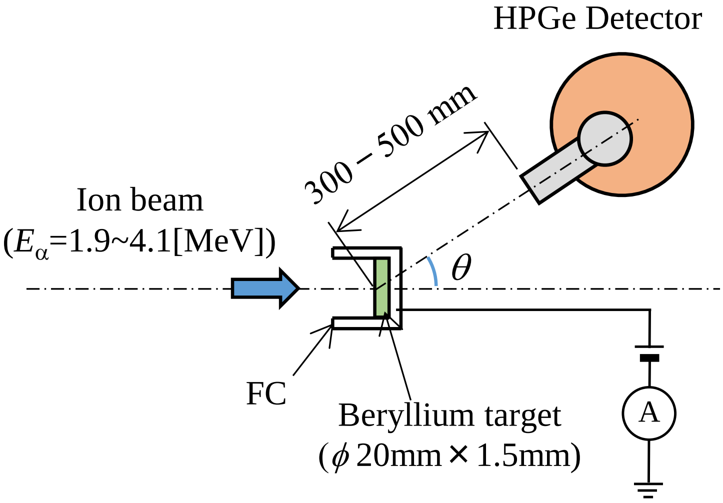


Fig. 1. Experimental set up

A Be target of 20 mm diameter and 0.1 mm thickness is set in a Faraday cup (FC). The FC was biased positive to restrict the secondary electrons. A current of the incident helium ions was measured by the FC, and it is typically 20 nA. To fix the incident area, the ions are limited by an aperture placed at the front of the FC. The aperture was also biased positive.

A HPGe was placed at the angle of θ, and the spectrum was measured. Since the excited nucleus in the reaction emits the gamma-ray before the nucleus stops, the gamma-ray spectra suffers from the Doppler effect. The effect is expressed as the following formula

$$\nu' = \nu \times \frac{\sqrt{1-(V/c)^2}}{1-(V/c)\cos\theta} \tag{3}$$

where ν is the original frequency of the gamma-ray, and ν' is the frequency after Doppler effect, V is velocity of the excited nucleus, and c is velocity of light. Introducing Planck's constant, h, equation (3) is expressed as the following

$$E_\gamma' = h\nu' = E_\gamma \times \frac{\sqrt{1-(V/c)^2}}{1-(V/c)\cos\theta}\,. \tag{4}$$

where E_γ is the original energy of the gamma-ray in Eq. (2), and E_γ = 4.439 MeV. E_γ' is the energy affected by the Doppler effect. A measured spectrum contains a total absorption peak, a single escape peak, and a double escape peak. In this paper we treat the total absorption peak. Since the HPGe detector has sufficiently high resolution, Doppler shift and broadening are detectable.

3. RESULTS AND DISCUSSIONS

3.1 Angular dependence of gamma-ray yield

Helium ions of 4.1 MeV are incident on a beryllium target, and the gamma-ray was generated. The angular dependence of the gamma-ray yield was measured by HPGe. Fig.2 shows the yield of the total absorption peak. The values are almost the same at θ = 30 ~ 90 [°]. The values at θ = 0 ~ 10 [°] are small and the values at θ = 15~ 16 [°] are large. The dependence shows the angular dependence of the reaction cross section, expressed in Eq (2). The differences are in ±40 %. In this paper, we treat mainly the shape of a gamma-ray energy spectrum, especially the total absorption peak. Since the dependence does not relate to a spectral shape (except yield), we do not discuss this in detail.

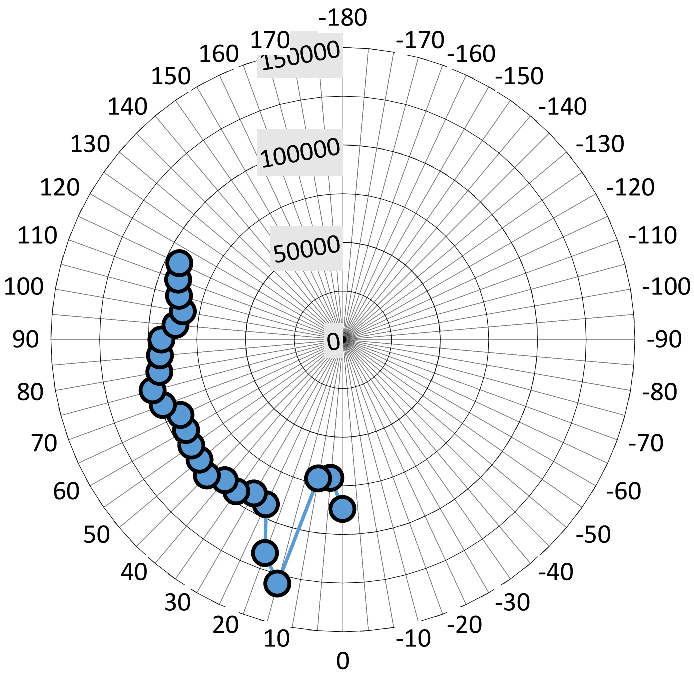
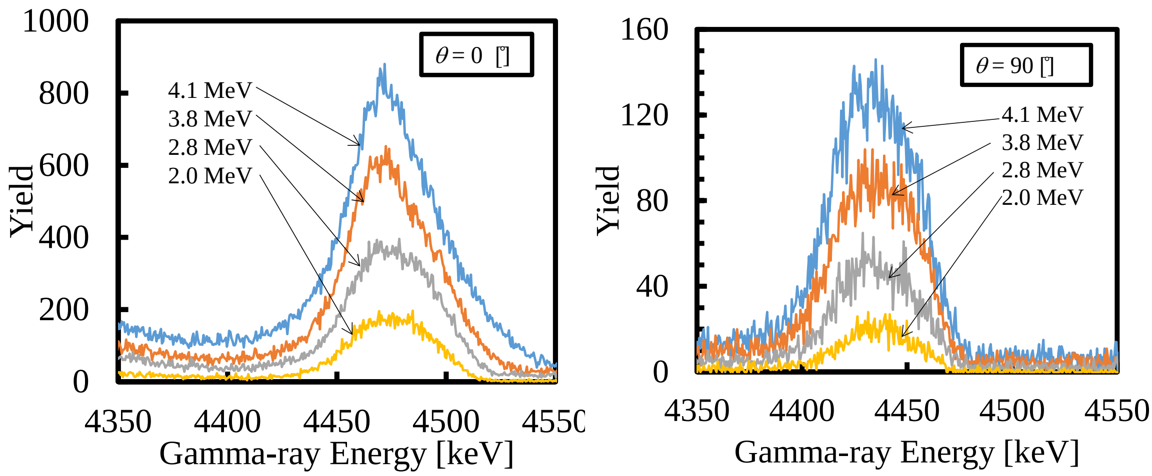


Fig. 2. Angular dependence of gamma-ray yield.

3.2 Incident energy dependence of the energy spectra

Energy dependence of the gamma-ray yield was measured at θ = 0 [°] and 90 [°]. The energy of the incident helium is 2.0, 2.8, 3.8, 4.1 MeV. Because the range of the helium ion increases as the energy increases, the yield for a high energy incidence is larger than that of a low energy. The experimental results are shown in Fig. 3. Neutron emits isotropic direction in the reaction, Eq. (2). Doppler broadening is caused by neutron emission. The energy resolution of HGPe is sufficiently large, and the width of spectra does not represent the detector resolution. All spectra are corrupt by the

Doppler broadening. The broadening does not have angular dependence. Fig. 3 (b) shows yield dependence on the incident energy, i.e., the projected range, but the shapes are almost the same. The shapes at $\theta = 0$ [°] change for the incident energy, because of Doppler shift. In this way, the shape of the gamma-ray energy spectrum changes for a detection angle. By analyzing the spectrum shape, the incident angle of α produced by Eq. (1) can be estimated as follows.



(a) $\theta = 0$ [°] (b) $\theta = 90$ [°]

Fig. 3. Energy dependence of the gamma-ray yield.

3.3 Doppler shift for the gamma-ray spectra

The Doppler shift was observed as functions of detection angle. The comparison between the spectra for the detection angle of $\theta = 0$ [°] and $\theta = 90$ [°] is shown in Fig. 4.

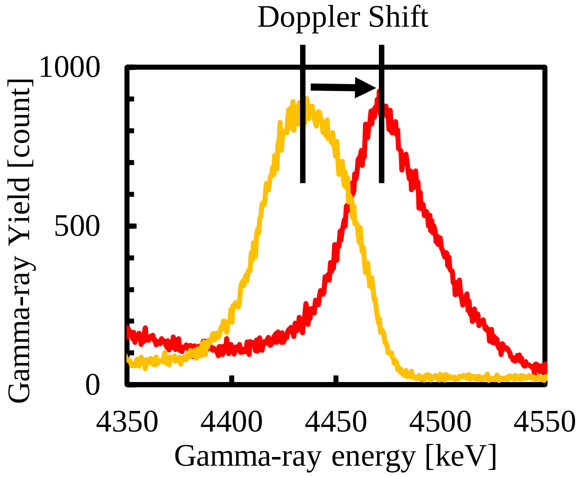


Fig. 4. An example of Doppler shift.

Because HPGe has a high energy resolution, the difference between two spectra is distinguished. If a lower energy resolution detector, such as a scintillator-type, is used, then the difference is not distinguished. The difference of the two peaks is 35 keV. It is convenient to use the difference in rough treatment. Since the spectral shapes are not the same for a different detection angle, a treatment includes the needed shape. We simulated the spectral shape using a computer simulation, and compared it with the experimental results.

3.4 Simulation procedure and comparison

A computer simulation of gamma-ray production was conducted using the following procedure. The energy of incident helium ion decreases in the beryllium target. The loss is calculated with the stopping power and the path length. A nuclear reaction between helium and beryllium occurs and an excited carbon-13, $^{13}C^{*}$, is created. The energy spectrum of the incident helium is similar to the reaction cross section that was reported by Kiptily (2010). The $^{13}C^{*}$ emits neutron immediately, and become $^{12}C^{*}$. It is supposed that the direction of neutron emission is isotropic. The $^{12}C^{*}$ emits a gamma-ray before it stops, and the lifetime was 42 fs. Because the lifetime is short, it is not taken into account in this simulation code. The Doppler effect is calculated by Eq. (4).

The simulation results are shown in Fig. 5. In this figure, one channel is corresponding to 0.5 eV. The width of the equipment, HPGe, the amplifiers, MCA, and so on, were not considered. The shape of high energy side at $\theta = 0$ [°] is similar to the structure of the reaction cross section. As the angle approaches 90°, the cross section structure disappears. Changes of this broadening is shown in Fig. 5.

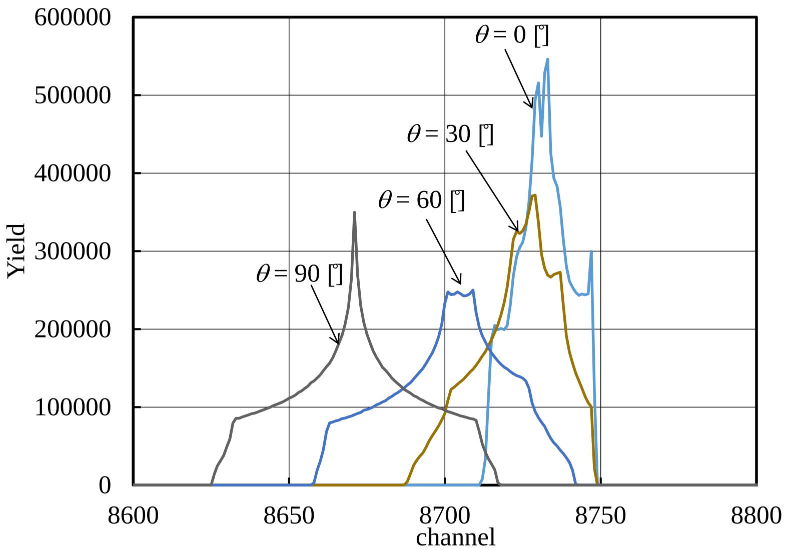


Fig. 5. Results of simulation shape at $\theta = 0, 30, 60, 90$ [°].

The comparison of these simulation results and the experimental results is shown in Fig. 6. The simulation results show the features of the experimental results. If the incident angle of fusion product, α, as has a specific direction and energy, the gamma-ray spectrum has a specific shape. The shape can be calculated by this simulation. It is considered that there is a capability for performing diagnostics on the escaping helium particles from the burning plasmas using a detector of high-energy resolution.

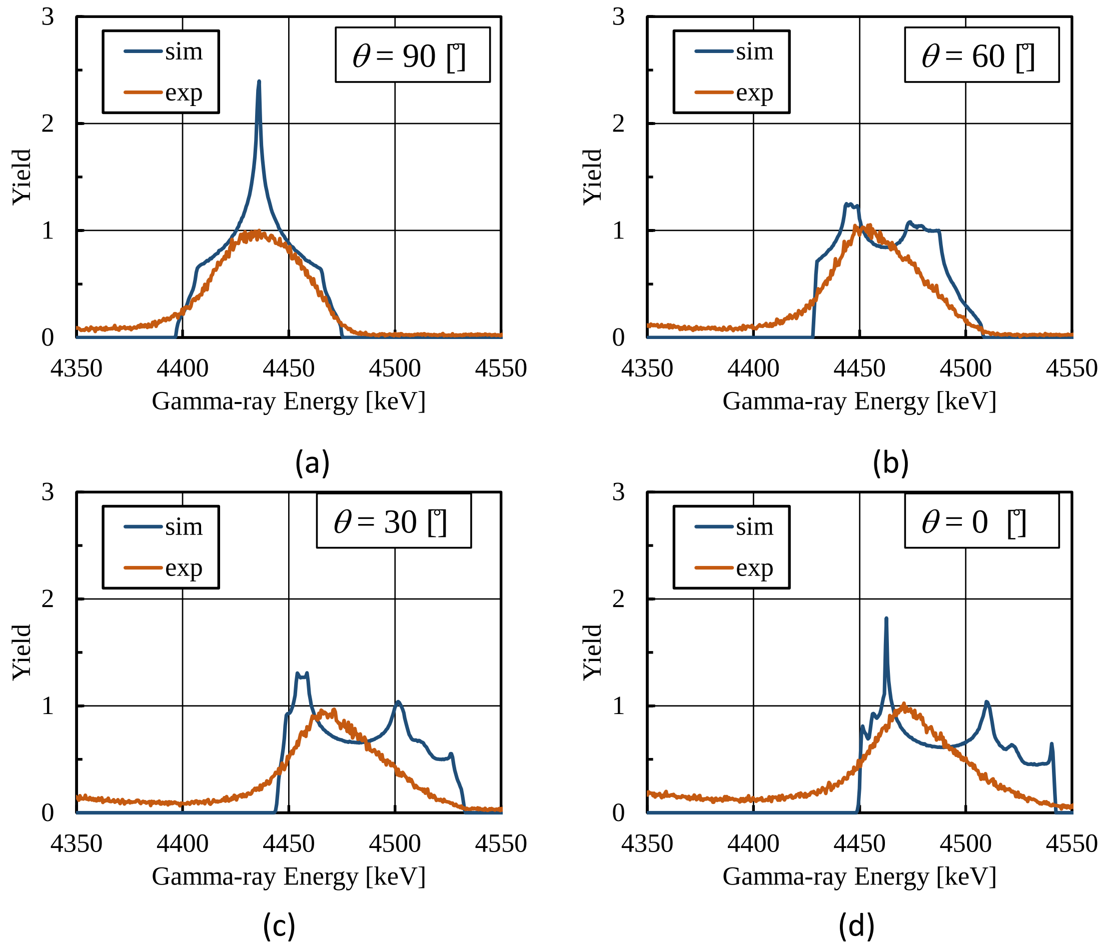


Fig. 6. Comparison between the simulation and experimental results.

4. CONCLUSION

In this study, high-energy gamma-ray spectra to diagnose the escaping helium from a fusion plasma were investigated. The reaction ^{9}Be (α, nγ) ^{12}C was demonstrated with the ion beam generated by a tandem accelerator. The angular dependence of the gamma ray yield was measured, and the cross section of the reaction was discussed. The energy spectra of the gamma ray were also measured with a HPGe detector. Since the excited nucleus in the reaction emits the gamma ray before the nucleus stops, the spectra of the gamma ray suffers from the Doppler effect. The Doppler shift and the broadening were observed as functions of detection angle. A computer simulation of the reaction including these effects was conducted. The comparison of these effects were in agreement with the experimental results. It shows that there is a capability for diagnostics on the escaping helium particles from burning plasmas using a detector of high-energy resolution.

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REFERENCES

Kiptily, V. G., Jarvis, O. N., Bertalot, L., Conroy, S. W., Popovichev, S., Mantisinen, M. J. and contributors to the EFDA-JET workprogramme (2001) *Gamma-Rays: Measurements and Analysis at JET*, JET European Fusion Development Agreement, EFDA-JET-PR(01)30

Kiptily, V. G., Cecil, F. E., Jarvis, O. N., Mantsinen, M. J., Sharapov, S. E., Bertalot, L., Conroy, S., Ingesson, L. C., Johnson, T., Lawson, K. D., Popovichev, S., and contributors to the EFDA- JET Workprogramme (2002) γ-ray diagnostics of energetic ions in JET, Nuclear Fusion 42 : 999-1007.

Kiptily, V. G., Baranov, Yu. F., Barnsley, R., Bertalot, L., Goloborod'ko, V., Hawkes, N. C., Murari, A., Popovichev, S., Sharapov, S. E., Stork, D., Yavorskij, V. and JET-EFDA contributors (2004) *Gamma-Ray Measurements of Fusion Alpha Particles in JET Trace Tritium Experiments*, 31st EPS Conference on Plasma Physics, London, 28 June -2 July 2004 ECA Vol. 28G, O-1.06 : 1-4

Kiptily, V. G., Cecil, F. E. and Medley, S. S., (2006) *Gamma ray diagnostics of high temperature magnetically confined fusion plasmas*, Plasma Physics and Control Fusion 48 : R59-R82

Gin, D. B., Pasternak, A. A. Kiptily, V. G., Chugunov, I. N., Shevelev, A. E. (2011) *Study of the $^{9}Be(\alpha, n\gamma)^{12}C$ reaction for the high temperature plasma diagnostics*,Transactions of Fusion Science and Technology, Vol. 60 : 16-21

Nishiura, M., Nagasaka, T., Fujioka, K., Fujimoto, Y., Tanaka, T., Ido, T., Yamamoto, S., Kashiwa, S. and Sasao, M. (2010) *Development and irradiation test of lost alpha detection system for ITER*, Review of Scientific Instruments 81, 10D313: 1-5

Nishiura, M., Doi, K., Taniike, A., Matsuki, T., Shimazoe, K., Mushiake, T., Yoshino, M., Nagasaka, T., Fujimoto, Y., Fujioka, K., Tanaka, T., Kisaki, M., Yamaoka, H., Matsumoto, Y., Wada, M. (2014) *Ion induced gamma ray detection for fast ions escaped from fusion plasmas*, Review of Scientific Instruments, 85, 11E804 : 1-3

Doi, K., Nishiura, M., Taniike, A., Matsuki, T., Shimazoe, K., Mushiake, T., Yoshino, M., Kisaki, M., Matsumoto, Y., Yamaoka, H., Kasuya, T., Wada, M. (2015)

Development gamma-ray imaging system for fusion device lost alpha diagnostics, Journal of Maritime Researches, Vol. 5 : 15-25

Kiptilyj, V. G., Matjukov, A. V., Mishin, A. S., Najdenov, V. O, Polunovskij, I. A., Rassadin, L. A. and Chugunov, I. N. (1991) *In-beam study of the $^{9}Be(\alpha, n_1\gamma)^{12}C$ reaction and alpha-particle diagnostics,* Fusion Technology, Vol. 22 : 454-460

Kiptily, V. G., Gorini, G., Tardocchi, M., de Vries, P. C., Cecil, F. E., Chugunov, I. N., Craciunescu, T., Gatu Johnson, M., Gin, D., Goloborod'ko, V., Hellesen, C., Johnson, T., Kneupner, K., Murari, A., Nocente, M., Perelli, E., Pietropaolo, A., Pinches, S. D., Proverbio, I., Sanchez, P. G., Sharapov, S. E., Shevelev, A. E., Syme, D. B., Yavorskij, V., Zoita, V. L., and JET-EFDA contributors (2010) *Doppler broadening of gamma ray lines and fast ion distribution in JET plasmas*, Nuclear Fusion 50 084001 :1-10